1989

ETSU-N-106

# Technology module for shoreline wave energy conversion in the UK

*Dr D J Martin*

ETSU

for the Department of Energy

ETSU N-106

# TECHNOLOGY MODULE FOR

# SHORELINE WAVE ENERGY CONVERSION IN THE UK

Dr D J Martin

Chief Scientist's Group
ETSU
Harwell Laboratory

April 1989
(Revised)

CONTENTS

# TECHNOLOGY MODULE FOR SHORELINE WAVE ENERGY CONVERSION IN THE UK

## EXECUTIVE SUMMARY


S1. This paper presents a technology module for the electricity-generating renewable technology of shoreline wave energy conversion. The paper adopts the methodology and presentational format of the 1986 Appraisal of Energy Research Development and Demonstration (Energy Paper 54 and ETSU-R43).

S2. Using the results of studies being conducted within the current Department of Energy R&D programme in this topic, together with information available from other UK and overseas work, it is possible to provide an economic categorisation and a tentative assessment of the achievable contribution of shoreline wave energy for electricity generation in the UK.

S3. The technology seems best suited to the supply of electricity to small isolated island communities such as those situated off the west and north of Scotland. It could also be used for central electricity supply as part of the grid system. In the case of isolated supply for island communities the technology at a resource size of 20 MW could be used as a supplement for diesel or gas-turbine generated electricity, when the operating and maintenance cost of supply is greater than 6p/kWh. In the case of central grid supply, the estimated achievable contribution of 250 MW would offer a benefit-to-cost ratio greater than one for Planning Scenarios I, II and III with a coal background only when the costs of transmission from wave power stations on the islands off west and north Scotland to the grid are excluded. When transmission costs are included, the technology offers an economic contribution to mainland electricity supply only in Scenario I. The technology would not be economic for central grid supply with a PWR background, in any circumstances.

S4. Tables S1 and S2 provide summaries of the Technology Assessment and the Appraisal of R,D&D for shoreline wave energy. If developed and deployed on the scale estimated, shoreline wave energy conversion could make a modest contribution to electricity supply for isolated island communities in future years. At present, however, it should be classed as a promising technology for these island communities. In particular, the achievable contribution, the economic prospects and the R,D&D expenditure prior to commercial deployment are not well defined.

Table S1. Assessment of Shoreline Wave Energy Technology

| Technical Feasibility | Economic Categorisation | | | Achievable Contribution | | Strategic Factors |
|---|---|---|---|---|---|---|
| | Market | Category | Time-scale | Scale | Limits | |
| Not yet demon-strated | Electricity generation | Promising for isolated communi-ties | Short/ medium | Value less than £1 bn | Could be constrained by environ-mental factor | Nuclear freeze $CO_2$ + other emissions |

Table S2. Appraisal of R,D&D for Shoreline Wave Energy Technology

| Motives | Cost-effectiveness | Other Factors |
|---|---|---|
| Economic<br>Strategic | R,D&D cost-effective in some but not all scenarios | Export possibilities |

# TECHNOLOGY MODULE FOR SHORELINE WAVE ENERGY CONVERSION IN THE UK

## 1. BACKGROUND

1.1 The Department of Energy's wave energy programme ran from 1974 to 1983. The feasibility of extracting energy from ocean waves was studied in detail and the work concentrated on the concept of an offshore wave energy station having a nominal installed capacity of 2 GW. In the 1982 Strategic Review of the Renewable Technologies it was concluded that the overall economic prospects for large scale offshore wave energy looked poor when compared with other electricity-producing renewable energy technologies. A further review in 1985 (ETSU R-30) confirmed this conclusion, and the Department accepted ACORD's advice to discontinue the large scale offshore wave energy R&D programme. The Department also decided it would continue to examine any specific devices which had the prospect of achieving the substantial reduction in costs necessary for commercialisation.

1.2 The Department has, therefore, continued to fund work on some specific topics in wave energy. One project is the development of small-scale wave energy converters at Queen's University, Belfast. This is based on the practical implementation of a 150 kW oscillating water column situated in a natural rock gully and driving a Wells turbine linked to an electrical generator. Further afield, the Norwegian Government is also supporting two 50 per cent shared cost projects with private industry in small scale wave energy conversion. One of these uses a 350 kW tapered channel/water turbine device and the other an oscillating water column similar to the Queen's University project but with an output of 500 kW. Both Norwegian devices are aimed at the extensive world market for supplying power to remotely situated island communities.

1.3 The residual UK activity in wave energy conversion has not so far been appraised in detail due to a lack of firm data. However, the technical and economic prospects for small-scale devices in favourable locations can now be examined in the light of information arising from these various R&D programmes. Although these programmes are still on-going, this paper has been prepared with the aim of providing an updated technology module for shoreline wave energy conversion. The paper adopts the methodology and presentation format of the

1986 Appraisal of Energy Research, Development and Demonstration. (see Department of Energy, Energy Paper 54 and ETSU R-43 HMSO, 1987).

1.4 This topic is of current interest to the CEGB and NSHEB. Both Boards view the prospects for shoreline wave power devices as being sufficiently promising to justify maintaining a watching brief on their potential for the UK.

## 2. GENERAL DESCRIPTION

2.1 One specific application of shoreline wave energy conversion envisages the generation of electrical power from a Wells turbine which is driven by the wave-induced motion of air. The device is based on the principle of a box mounted vertically in the water, open at the bottom and with an orifice in the top. Incident waves cause the water level in the box to rise and fall, thereby forcing air contained in the box through the orifice to drive the turbine. Such oscillating water column devices have been studied in detail for the offshore wave programme, but are equally applicable to wave power stations which make use of waves incident on the shoreline.

2.2 For a shoreline application, the energy conversion device is located at the interface between the ocean and a land mass. Either a natural rock gully or a purpose-built channel provides the necessary wave capture and, by focussing the wavefront, concentration of the available energy can be achieved.

2.3 In contrast with offshore wave energy converters, the shoreline device would have a relatively small electrical capacity, of the order of 0.1 to 1.0 MW, depending on the wave power available in the wave capture site. The shoreline location means that construction costs per unit of capacity can be substantially lower than for offshore devices. This is because offshore devices would need to be designed to survive the large dynamic and static loads occurring in the ocean, whereas shoreline devices would not be subject to such high loadings. In addition, transmission costs are lower since there is no need for underwater cabling and the distances to the nearest connection point would be much shorter. Furthermore, a shoreline wave power station would have to survive a somewhat less hostile environment than its offshore equivalent and so maintenance costs would be lower. Access to a shoreline wave power station would be considerably easier than to an offshore installation.

2.4 These small-scale wave energy devices are claimed to be cost-effective for supplying power to isolated island communities, where the cost of conventional electrical power is high. A shoreline wave power station could be used as a supplement for diesel or gas-turbine generation in such locations.

2.5 Oscillating water column driven Wells turbine devices have so far found application in providing power for navigation buoys at around 100W power output. A market is now beginning to develop for this equipment which has successfully proved its technical feasibility. Clearly, the uplift in power output by a factor of at least 1000 for the generation of commercial electricity supplies would be a major step.

## 3. CURRENT STATUS OF R,D&D

3.1 There is a relatively modest level of R,D&D activity in this topic. At present, oscillating water column systems are being studied in a number of overseas locations in order to assess the technical and economic features of shoreline devices.

3.2 A feasibility study has been carried out by Queen's University of Belfast for the Department of Energy. The study has examined the design of a shoreline wave energy device on the Island of Islay in the Inner Hebrides. This design incorporates the best features of shoreline wave energy conversion, namely an oscillating water column device which would drive a two stage Wells turbine of 150 kW output at a natural rock gully site identified in the feasibility study. The next stage of this project is the building and testing of a prototype oscillating water column structure in order to demonstrate the feasibility of the construction method and to determine the pneumatic performance of the device.

3.3 Kvaerner-Brug in Norway have constructed a multi-resonant oscillating water column/Wells turbine wave power station at a prototype test site on the Island of Toftestallen, northwest of Bergen. The power output is 500 kW, and the device has been in operation since late 1985. (The prototype was destroyed by a storm in December 1988). A second prototype system nearby comprises a 350 kW tapered channel device which utilises wave focussing effects to drive a low head water turbine. This system has been built by the Norwave company. Both Norwegian schemes depend on special geographical conditions such as a steep cliff face with deep water immediately below it for the oscillating water column device and a natural geological formation, together with significant civil engineering, for the tapered channel device. Operating experience is being achieved with both devices and some information on performance is available to the research community (see paragraph 4.3).

3.4 An American experimental wave power device, Neptune, is mounted in shallow water quite close inshore. The device utilises an oscillating water column with a mechanical piston to drive a pump arrangement. No performance data are available for this device.

3.5 Several other countries are investigating or developing wave power devices either for navigation buoy applications or for electricity generation. It is known that Australia, Portugal, India, China, Japan and Ireland are interested in the development of either wave power stations or navigation buoy applications. These countries are carrying out R&D or feasibility studies in these topics, but no practical installations have so far been reported.

3.6 Table 1 lists the planned expenditure in 1987/88 by UK organisations on their wave energy R,D&D. Table 2 lists the available data for other countries.

## 4. TECHNOLOGY APPRAISAL

4.1 Technical feasibility: The technical feasibility of shoreline wave energy conversion has not been demonstrated in a practical application in the UK. The prototype installations in Norway are providing operating experience under conditions somewhat different to those in which the technology would be employed in the UK. The Islay device is located in shallow water with depths of the order of 10m, whereas the Norwegian prototype is a deep water device located on a shear rock face with 50m of water depth.

4.2 The principal technical issues to be resolved are:-

- the feasibility of the construction method and the accuracy of the structural design
- the permanence of the wave focussing conditions
- the pneumatic performance of the device
- the performance of the two-stage Wells turbine
- the reliability of the turbine in an operating environment
- the control of the electrical output and its integration with conventional electrical supplies.

4.3 These issues will be addressed by the proposed prototype demonstration device on Islay. Once the results of this demonstration have been assessed, it should be possible to establish the technical feasibility of the concept. However, present indications from the Norwegian prototypes are that water ingress to the turbine must be avoided, that the turbine must have a good starting performance and that the physical integrity of the rock gully must be maintained.

4.4 Shoreline wave energy converters located on islands off the west and north coast of Scotland could be adopted at two levels of system complexity:

(A) electricity supply for those isolated island communities, which are not connected to the grid, and where the wave energy converters are used as a supplement for diesel or gas turbine generating plant;

(B) electricity supply for use across the whole NSHEB/SSEB area, where the wave energy converters are connected to the mainland grid system, and are used as part of the central supply. This option could also apply to shoreline wave energy converters located on the South-Western Peninsula of England, and supplying power to the CEGB

4.5 Both levels of complexity could be deployed once the basic technical feasibility is established. As with the offshore wave energy concept, it is likely that AC power would be generated by individual devices at a variable frequency with an intermediate conversion stage involving rectification and inversion. This would allow connection at 50 Hz frequency to either a local non-grid network or the mainland grid system. The electrical engineering requirements of such an arrangement would not pose any significant technical problems. It should be noted, however, that System B may involve the construction of transmission lines. Power from the Western Isles would need to be transmitted to the NSHEB grid. This may involve a 275 kV single circuit to Beauly (near Inverness) on the mainland, submarine cables between Skye and the islands and transforming sites on the islands themselves, but the existing 132 kV single circuit to Broadford on Skye would have sufficient capacity to transmit some of the power available from shoreline wave energy stations on the Western Isles. It should be noted that NSHEB have plans to construct a grid connection between Skye and the Western Isles for the purpose of delivering power to the islands, and this link could also have sufficient capacity for taking some power from wave energy converters on the islands. A modest backfeed of about 30 MW could be accommodated. This would allow an installed capacity of between 40 and 60 MW of shoreline wave power on the Western Isles since some power would be used on the islands themselves. However, some strengthening of and additions to the grid connections would be needed if the full potential resource on the islands were to be exploited. On the other hand, few additional transmission facilities would be required for power from the South-Western Peninsula of England.

4.6 Economic prospects: Present estimates for the unit production costs of electricity from shoreline wave energy devices in natural rock gullies are about 5p/kWh (including local connection to the electricity distribution grid). These costs are derived from the Islay project data for the capital, operating and maintenance costs of a 1 MW device, and are based on the design for the

Islay prototype (but assume that costs could be reduced by about 30 per cent for commercial devices). The costs of transmission impose further production costs of between 1.0 and 1.8p/kWh assuming that it is necessary to construct transmission facilities specifically for the exploitation of 150 MW of power between the Western Isles and Beauly. The cost ranges arise from the uncertainty associated with the productivity of the device, the lower figures referring to a 30 per cent annual load factor and the upper figures a 17 per cent load factor.

4.7 Thus, the annual load factor is an important characteristic of a wave power system. 17 per cent is a realistic value which is based on offshore wave energy data, device availability and the overall station efficiency. 30 per cent is a more optimistic value which makes some allowance for the possibilities that the device performance might improve as designs are refined, and that the shoreline location offers a higher availability for wave energy conversion, since the shoreline device would operate with a narrower wave energy spectrum than an offshore device.

4.8 If a 30 per cent annual load factor can be achieved in commercial applications, shoreline wave energy costs would be comparable with diesel and gas-turbine generator costs in System A defined above. This is because the operating and maintenance cost in Spring 1989 of diesel and gas-turbine generated electricity for the islands off west and north Scotland is around 6p/kWh. Capital outlay for a wave power station based on the Islay costings with around a 17 per cent load factor would be about £900/kW installed capacity and this is also comparable with replacement capital costs for non-grid electrical plant. (The Norwegian oscillating water column device has an estimated cost of around £1000/kW installed capacity.) However, the costs for wave energy are not sufficiently competitive at present marginal electricity costs for there to be an overwhelming case for investment in the technology by organisations such as NSHEB. It is more likely to be viewed as a means of supply diversification at a cost similar to the provision of conventional electrical supply for non-grid connected islands. Only if electricity costs on the relevant islands rise will shoreline wave energy become an attractive investment option.

4.9 To evaluate the economic benefits of utilising power from shoreline wave energy conversion as part of the central electricity generating system, the

Harwell Electricity Planning model, HELP, can be used. Appendix I provides a brief description of the procedures involved which are explained more fully in ETSU R-43. The benefit-to-cost ratios in System B defined above are shown in Table 3, using the planning Scenarios I, II and III and the 1985 constant price Scenario* adopted in ETSU R-43. The cost of constructing a transmission line from the western isles to the grid connection at Beauly on the mainland is presented as an inclusive and an exclusive item in these calculations. In this way, a comparison between the possible exploitation routes with and without the need for specific transmission facilities can be made. It can be seen that the technology offers a benefit-to-cost ratio greater than 1 in Scenarios with a coal background when the transmission costs are excluded and with rising fossil fuel prices. When transmission costs are included, only Scenario I offers a benefit to cost ratio greater than one. The technology is not economic with a PWR background in any Scenario.

4.10 To illustrate the lowest boundary for economic attractiveness, the target capital cost for 1985 constant prices in order to meet the benefit:cost ratio of unity has been calculated for the coal background. For this situation, the targets are £520/kW when transmission costs are excluded, and £270/kW when transmissions costs are included. Other Scenarios would allow higher breakeven capital costs (in a coal background).

4.11 <u>Achievable contribution</u>: The potential shoreline wave power resource in the UK is determined by the number of sites with both a sufficiently productive offshore wave climate and a suitable local sea-bed and shoreline topography.

4.12 The work carried out within the DEn wave energy programme can help identify the areas which are likely to have the necessary offshore wave climate. The most likely areas are the West and North Coasts of Scotland and the South Western Peninsula of England where the offshore average annual wave power is in excess of 30 kW/m. As waves approach the shore they are usually attenuated due to friction with the sea-bed and the extent of this attenuation will be an important factor in determining the technical potential for shoreline devices. However, there will be locations where the sea-bed and the shoreline topography have a focussing effect such that the wave height

---

*The fuel price assumptions for these scenarios are also listed in Appendix I.

approaching the shore is amplified rather than attenuated. It is known that in favourable sites the amplification factor can be as much as four-fold. For example, the preferred gully on Islay has an average annual power of 20 kW/m as compared with an average in the nearby bay of 5 kW/m. Thus a measurement of offshore wave power does not necessarily indicate the magnitude of the shoreline wave power at any given location.

4.13 An additional factor is the tidal range experienced at the site. Ideally, the site should have a restricted tidal range of no more than 1 to 2m so that the pneumatic capacity of the device does not have to cope with a wide variation in water level. Otherwise, the column structure costs could become excessive and make the device uneconomic.

4.14 The shoreline site should also involve minimal civil works, access from the landward side must be adequate to facilitate construction, and a point of connection to the local electricity network must not be too distant.

4.15 With the large number of constraints on the potential for the shoreline wave power resource and the lack of knowledge about amplification effects, it is not possible to identify either the technical potential or the achievable contribution with much precision. However, a rough estimate can be made by an examination of the Admiralty Charts for the promising areas and by extrapolating the results from the feasibility study for Islay. This procedure reveals the following tentative results for the islands off west and north Scotland and for the South Western Peninsula of England:-

| Island | Seaboard suitable for wave power sites (km) | Shoreline Wave Energy Technical Potential (MW) |
|---|---|---|
| Islay | 20 | 30 |
| Inner Hebrides | 40 | 60 |
| Outer Hebrides | 100 | 150 |
| Shetlands | 60 | 90 |
| Orkneys | 50 | 75 |
| South West Peninsula | 120 | 180 |
| Totals | 390 | 585 |

4.16 These estimates are made using a maximum line density of 1.5 MW/km of seaboard suitable for wave power sites using natural rock gullies. Sites on the South Western Peninsula could be less attractive than those on the Scottish islands due to the larger tidal ranges experienced in this area. Given this and the other constraints described above, the achievable contribution is a subset of the technical potential. For the purposes of this paper, a value of 250 MW is assumed for the achievable contribution of which 170 MW is assumed from the Inner and Outer Hebrides, and 80 MW from the South West Peninsula. It should be noted that these values are subject to considerable uncertainty due to the incomplete data on which they are based. However, the values do serve to indicate the relatively small size of the resource when compared with some other renewable technologies.

4.17 The achievable contribution would be increased substantially if use could be made of man-made rock gullies. These would be formed by excavating suitable sites using rock blasting or rock drilling techniques which may be similar to those employed on the Norwegian wave energy project. Any seaboard with a rockface, no beach and either a suitable offshore wave climate or with seabed topography which enables wave focussing to occur could be exploited in this way. However, at present (April, 1989), the costs of constructing a man-made gully have not been determined and it is not possible to assess whether this option offers a more cost-effective route to exploitation.

4.18 <u>Institutional barriers</u>: The uptake of the technology, even for small scale deployment, will depend on investment decisions by the Generating Boards and by private suppliers. Thus, these organisations will have to be convinced of the technical feasibility and the economic prospects before shoreline wave energy can make a contribution to electricity generation. The Boards will also be concerned about the integration and control of a multitude of small, dispersed power stations into the electricity supply network. However, the experience of the North of Scotland Hydro-Electric Board in operating its 1.1 GW of hydroelectric capacity at over 60 locations would be relevant to this aspect of the technology.

4.19 Public acceptance of small-scale wave energy converters, often located in remote areas of scenic beauty, will also be required before the Boards or private suppliers proceeded to implement the technology.

4.20 Environmental, health and safety issues: The major environmental impacts of shoreline wave power stations are likely to be noise disturbance and visual intrusion. The degree of importance of these impacts will depend on the location, i.e. the proximity of permanent residences, the perceived scenic beauty and the presence of other natural or man-made sound generating and visual features. Where required, the choice of transmission route through scenic areas of both the islands and the mainland will also require careful planning in order to establish the most acceptable way-leave.

4.21 Shoreline wave energy is not expected to impose any health and safety issues other than the occupational hazards of constructing and maintaining equipment on exposed and remote locations.

4.22 Cost-effectiveness of R,D&D: A demonstration of a prototype device may shortly commence on Islay and further development of the Wells turbine with particular reference to the performance of two stage machines is likely. Expenditure on these R,D&D activities will help to confirm the technical feasibility of the device, but it is not possible to ascertain the national cost-effectiveness of the R,D&D because no thorough estimates of the number of suitable sites in the UK are yet available. Some modest R&D expenditure aimed at investigating suitable coastlines is desirable in order to assess incident wave climates, local focussing effects and construction suitability so that a better understanding of the extent of the resource can be established and a survey of the economic potential for shoreline wave energy is being carried out at present.

4.23 Further development led by manufacturers of turbine/generator equipment suitable for the electricity supply industry is also desirable to optimise performance and to reduce manufacturing costs. There would clearly be benefits from a well-founded knowledge of the functioning of production scale devices. These would most likely be 500 kW turbines, offering scope for modular construction of multiples of this output size. If this research is successful then a demonstration of a 500 kW device would be a logical next step in which an industrial contribution from an equipment supplier would be desirable.

4.24 The total R,D&D expenditure to completion of a comprehensive programme over several years involving equipment suppliers and electricity utilities is estimated by ETSU to be around £2M (1985 prices).

4.25 An indication of the cost-effectiveness of R,D&D can be made for the two systems A and B. If the deployment of shoreline wave energy is limited to the provision of electricity for isolated island communities (System A above), the achievable contribution is likely to be around 20 MW because it would not be economic to invest in supplementary capacity at a level greater than this. The figure of 20 MW is based on the assumption that the renewable resource would be restricted to be no more than 30 per cent of the maximum demand on the relevant islands, (namely the Outer Hebrides and Shetland) which is about 70 MW. In this situation shoreline wave energy would be utilised as a means of reducing fuel oil costs for a proportion of the year, determined by the annual average load factor. There would be no change in the installed capacity of diesel or gas-turbine plant on the islands. However, it should be noted that the inclusion of a wave power station can lead to an increase in part load operation of the diesel plant, thus giving rise to a loss of diesel efficiency and possibly increased maintenance cost. These second order effects have not been calculated in this assessment, but would tend to reduce the attractiveness of a wave power station.

4.26 The contribution which shoreline wave energy conversion can make in this deployment situation is proportional to the load factor achievable and the marginal electricity price of diesel or gas-turbine generated electricity. Table 4(a) lists the returns calculated for a range of operating and maintenance costs (assumed constant in real terms over the plant lifetime) using fuel oil and for 30 per cent and 17 per cent load factors. The fuel oil costs would include delivery to the Scottish islands and are not, therefore, directly related to those used in the 1986 Appraisal Scenarios. However, the values used are representative of the range of fuel costs covered by the Scenario assumptions. Given R,D&D costs of about £2M, and capital investment costs of around £6.5M present value in 1985 prices, the technology would be attractive only for marginal prices greater than 6p/kWh and with load factors better than 17 per cent.

4.27 If the deployment of shoreline wave energy is taken up as a contribution to mainland electricity supply (System B above), the maximum achievable contribution is estimated to be about 250 MW. Table 4(b) lists the returns from this contribution. Note that the transmission costs are shown as both excluded and included in these calculations. It can be seen that the technology offers a modest return on R,D&D only for planning Scenario I with a coal background and constant prices/demand post 2010, and when transmission costs are excluded.

4.28 As was done in the 1986 Appraisal, the sensitivity of the returns to a future in which prices/demand continue to rise to 2030 was examined and this is shown in Table 4(c). In this situation, deployment of the technology is cost-effective for Scenarios I and II with a coal background and when transmission costs are excluded.

4.29 When transmission costs are included, the returns from deployment are considerably reduced, and the technology is cost-effective only in Scenario I for prices/demand rising to 2030 in a coal background.

4.30 The technology is not cost-effective with a PWR background in any circumstances. It should be recognised, however, that the 250 MW resource size is only a tentative estimate. If a larger achievable contribution could be realised in practice, for example, by the use of man-made rock gullies, the technology would provide a more attractive return on its R,D&D costs in the Scenarios listed above. On the other hand, a smaller achievable contribution would reduce still further the attractiveness of the technology.

4.31 Timeliness of R,D&D: In view of the promising economic prospects for shoreline wave energy conversion in isolated island communities with high marginal costs using diesel or gas-turbine plant for electricity supply, it is timely to conduct a modest level of R,D&D activities over the next 10 years with a view to stimulating deployment in due course.

4.32 Export potential: The Norwegian programme of shoreline wave power has, as its commercial basis, the aim of developing a market for wave power converters of around 150 kW for remote island communities. Islands in the Pacific Ocean have been identified as a likely market. If UK work proves successful, there are good prospects for turbine manufacturers and consultants to sell their services in this market.

4.33 Scope for international collaboration: An IEA collaborative programme on wave energy offers the UK an opportunity to keep in touch with developments elsewhere. Links have been established with the Norwegian programme and these can be cultivated for mutual benefit.

4.34 Import possibilities: The Norwegian companies which have already tested prototype devices are establishing a commercial lead in the technology. With the growth of a modest world-wide interest in wave power, shoreline devices will probably be developed further and deployed overseas irrespective of their UK prospects. Import of the technology will almost certainly be a possibility if UK companies do not develop the technology and there proves to be a viable market in the UK.

4.35 Technological excellence: The substantial investment in offshore wave energy R&D over the last 10 to 12 years has enabled the UK to become a world leader in several aspects of wave power technology. Many of these aspects can be applied to shoreline devices, e.g. wave tank testing and turbine design. Furthermore, the techniques being developed for wave power measurement, site surveying and resource modelling offer further scope for technological leadership.

## 5. SUMMARY AND CONCLUSIONS

5.1 Table 5 presents a summary of the main findings of this technology appraisal. Based on the information presently available, shoreline wave energy conversion using natural rock gullies appears to be a promising technology for small scale application in isolated island communities but there are some uncertainties associated with it. In particular, the achievable contribution, the economic prospects and the R,D&D expenditure prior to commercial deployment are not well defined.

5.2 The technology could be developed at a variety of sizes from small units of around 100 kW to larger units of 1 to 2 MW. However, a standard turbine size equivalent to 500 kW output would be desirable, with modular construction employed for multiples of this unit. Sites with a capacity of less than 500 kW are unlikely to be developed because they would probably prove uneconomic.

5.3 Shoreline wave energy at these scales of operation estimated in this Appraisal may fulfil a commercially attractive niche. However, the technology is not likely to see widespread deployment on a national scale because the available resource is confined to relatively few locations on the western and northern islands off Scotland. Once the technology is fully developed isolated island communities could benefit from its introduction provided that the economics are sufficiently attractive, and if deployment was initiated, sites in these locations would probably receive the most attention. NSHEB would have an interest in pursuing this route as a means of reducing its expenditure on fuel oil for non-grid electricity supply, and private suppliers may see opportunities for developing a market in remote communities.

5.4 The technology is only marginally economic as a central electricity supply resource with rising fossil fuel prices if the costs of transmission from the islands to the grid have to be included in the calculations. In a situation where sufficient transmission facilities are available, such that the capital costs of transmission are already accounted for, then the technology would be economic in a coal background and with increasing fossil-fuel prices. On the other hand, the technology would offer a modest contribution to isolated island supply, if it is deployed to the extent estimated in this Appraisal. With this in mind, it would be prudent to allocate R,D&D expenditure with care, since the returns on R,D&D are somewhat modest and are subject to uncertainties which cannot be resolved at the present time.

## 6. REFERENCES

6.1 The following literature sources were consulted during the preparation of this report.


Background information

(i) "Energy Technologies for the United Kingdom: 1986 Appraisal of Research, Development and Demonstration" Energy Paper 54 and ETSU R-43, Chief Scientist's Group, ETSU. HMSO, 1987

(ii) "Wave Energy. The Department of Energy's R&D Programme 1974-1983" ETSU R-26, P.G. Davies et al, ETSU. HMSO, 1985

(iii) "Ireland's Wave Power Resource", June 1982, Dr. D. Mollison, National Board for Science and Technology/Electricity Supply Board.

(iv) "Prospects for the exploitation of the renewable energy technologies in the United Kingdom", ETSU R-30, Chief Scientist's Group, ETSU. HMSO, 1985

Shoreline Wave Energy Technology

(v) "Small-Scale Low Cost Wave Power Devices Phase I", January 1987. Dr. T.J.T. Whittaker et al, Queen's University of Belfast.

(vi) "Queen's University, Belfast O.W.C. Device Study", March 1987. Rendel, Palmer & Tritton.

(vii) "The Economic Analysis of Wave Energy", ETSU L-7, October 1984. H.G. Tolland and J.F. Walker, ETSU.

(viii) "Norwegian Visit" December 1984, Dr. P.R.S. White, SEA-Lanchester Wave Energy Group.

(ix) "Recent Developments in Wave Energy Systems". Dr. T.J.T. Whittaker. Energy Options Conference, Reading 1987.

North of Scotland Hydro-Electric Board System

(x) "North of Scotland Hydro-Electric Board, Report and Accounts 1985/86", June 1986. Generating Stations map and "Power from the Glens", NSHEB brochure (undated).

Table 1. UK R,D&D Programmes on Shoreline Wave Energy Planned Expenditure in 1987/88

| | £M |
|---|---|
| Government | 0.15 |
| Nationalised Industry | Small |
| Private Industry | - |
| University | Small |

Table 2. Overseas R,D&D Programmes on Shoreline Wave Energy Planned Expenditure in 1987/88

| | £M |
|---|---|
| Norway | ~ 1 |
| Japan | ~ 0.5 |
| United States | Small |
| Portugal | Small |

## Table 3 Technology Characterisation

### Shoreline Wave Power

| Assumptions: Central Generating Resource | |
|---|---|
| Plant type | Oscillating Water Column in Rock Gully |
| Discount rate | 5% |
| Plant life | 25 years |
| Load factor | 30% - 17% |
| Capital costs | 2.8-4.5 p/kWh |
| Running costs | 0.6-1.1 p/kWh |
| Transmission costs (if grid connected) | 1.0-1.8 p/kWh |
| Achievable contribution | 250 MW |
| Build rate | 25 MW/year |
| Deployment date | 2001 |

Benefit: Cost Ratio: Prices/demands constant post 2010; Load factor 30%

| Scenario | PWR Background | | Coal Background | |
|---|---|---|---|---|
| | Transmission Costs | | Transmission Costs | |
| | Excluded | Included | Excluded | Included |
| I | 0.9 | 0.6 | 1.6 | 1.0 |
| II | 0.8 | 0.5 | 1.3 | 0.9 |
| III | 0.6 | 0.4 | 1.1 | 0.7 |
| 1985 Constant | 0.5 | 0.2 | 0.6 | 0.4 |

Table 4(a) Returns from Deployment

of 20 MW Resource (System A)

Returns (£M) as a function of:
Illustrative operating and maintenance costs for electricity generation using fuel oil, deployment date 2001

| Operating and maintenance costs p/kWh | Returns £M PV in 1985 | |
|---|---|---|
| | 17% load factor | 30% load factor |
| 3 | * | * |
| 6 | * | 10 |
| 9 | 3 | 15 |

Estimated R,D&D cost to commercial deployment: £2M (1985 Prices)

*In these circumstances, the returns are negative since there are no savings from the installed capacity.

Table 4(b) Returns from Deployment of 250 MW Resource (System B): Prices/demands constant post 2010

R,D&D Returns, PV in 1985 £M:
Deployment date 2001; load factor 30%.

| Scenario | PWR Background | | Coal Background | |
|---|---|---|---|---|
| | Transmission Costs | | Transmission Costs | |
| | Excluded | Included | Excluded | Included |
| I | * | * | 20 | * |
| II | * | * | * | * |
| III | * | * | * | * |
| 1985 Constant | * | * | * | * |

Table 4(c) Returns from Deployment of 250 MW Resource (System B): Prices/demands rising to 2030

R.D&D Returns, PV in 1985 £M:
Deployment date 2001; load factor 30%.

| Scenario | PWR Background | | Coal Background | |
|---|---|---|---|---|
| | Transmission Costs | | Transmission Costs | |
| | Excluded | Included | Excluded | Included |
| I | * | * | 50 | 20 |
| II | * | * | 20 | * |
| III | * | * | * | * |
| 1985 Constant | * | * | * | * |

Estimated R,D&D Cost to commercial deployment £2M (1985 prices)

*In these scenarios, the returns are negative since there are no savings from the installed capacity.

Table 5 Summary of Technology Appraisal

Shoreline Wave Energy Conversion

| | |
|---|---|
| Technical Feasibility: | Not yet established under UK operating conditions, but operating experience is being obtained in Norway. |
| Economic Prospects: | Marginally economic for isolated islands and in medium and high price scenarios compared with fossil fuel fired generation. Marginally economic as a central electricity supply resource when transmission costs to the mainland grid are excluded. When transmission costs are included, the economics become poorer. |
| Achievable Contribution: | A tentative estimate, based on extrapolating the survey data for the Islay prototype, gives a value of 250 MW for central electricity supply. For isolated island supply, 20 MW is estimated. |
| Institutional Barriers: | For deployment in large numbers, the Generating Boards and possible private suppliers for remote communities would need to be convinced of public acceptability and commercial prospects. |
| Environmental Health & Safety Issues: | Noise disturbance and visual intrusion will require attention. |
| Cost-effectiveness of R,D&D: | Cost-effective for isolated islands assuming a fossil fuel fired background and medium to high fuel prices. |
| Timeliness of R,D&D: | Modest R,D&D is required over the next few years to reduce costs, to improve performance and to develop suitable site identification methods. |
| Export Potential: | Some scope for exports of turbines and of technical know-how to markets in locations such as the Pacific Ocean. |
| Scope for International Collaboration: | Links with IEA and Norwegian projects could be cultivated for mutual benefit. |
| Import Possibilities: | Norwegian commercial devices may find application in the UK, if UK companies do not develop the technology and there proves to be a viable UK market. |
| Technological Excellence: | UK is world leader in several aspects of wave power technology such as wave tank testing, turbine design and survey methods. |

## APPENDIX 1

### METHODOLOGY

A.1 It is useful to outline the methodology used for the electricity production technologies since it differs in a number of respects from that used elsewhere in the Appraisal. The appropriate division of the electricity market between competing generating technologies has been evaluated with the aid of the Harwell Electricity Planning model, HELP. This model has been described in ETSU R-13 (Volume II, Appendix 8) and has since been modified to meet the needs of the present study. It calculates the total discounted cost of satisfying a prescribed demand for electricity during a specific period. The key task in that calculation is to define for that period an appropriate plan for building new generating plant. This plan is assembled in four stages: (i) particular capacity may be commissioned between definite dates; (ii) the building plan is restricted to a limited portfolio of plant types; (iii) various constraints may be imposed upon the building plan; (iv) within these restrictions, the HELP model identifies a building plan that ensures that prescribed demand is satisfied at minimum total discounted cost. The calculation of this cost, and of the optimum building plan, depends upon various specific assumptions: (i) electricity demand during the specific period; (ii) the capacity and remaining life of all plant in service at the beginning of that period; (iii) the working life of new plant; (iv) the availability of any plant that supplies electricity; and (v) the unit capacity and operating costs characteristic of each type of generating plant.

A.2 The approach adopted in this Appraisal is first to assess the technology and then to appraise the corresponding RD&D programme. To achieve these objectives, the HELP model is used in two distinct but closely related modes:

(a) Technology Assessment

(i) The HELP model is first used to reckon, for definite plant costs and performance, the total discounted cost of satisfying a prescribed demand for electricity; the plant portfolio excludes the plant under assessment. The result of this calculation represents a baseline for the assessment.

(ii) The calculation is repeated, with the same demand, cost and performance data; the building plan now specifies the construction between definite dates of a fixed capacity of the shoreline wave energy plant under assessment, but is otherwise restricted to the same plant portfolio.

(iii) A benefit/cost ratio is calculated from the difference between these results ($\Delta H$) and from the capital (K) and operating costs (E) of the plant under assessment, discounted to 1985 prices. The benefit/cost ratio $\equiv \frac{\Delta H - E}{K}$.

(b) <u>RD&D Appraisal</u>

(i) The HELP model is first used to reckon the total discounted cost of satisfying a prescribed demand for electricity, by assuming costs, performance and a plant portfolio that take no account of benefits derived from the RD&D to be appraised. This result represents a baseline for the appraisal.

(ii) The calculation is repeated with modified unit costs or availabilities, or with extended plant lives, or with an expanded plant portfolio; these changes acknowledge improved or innovative technologies derived from RD&D.

(iii) The difference between these results represents the returns from the necessary RD&D expenditure, and is used in evaluating the cost effectiveness of the programme.

A.3 Calculations have been carried out for four energy-price and demand scenarios adopted in the Appraisal. There is a substantial RD&D effort in the electricity-producing technologies undertaken at least in part for strategic objectives and in order to examine a wider range of futures, the Appraisal also looked at the effect of both rising energy prices and demand between 2010 and 2030, and also constant price and demand during that interval.

SCENARIOS

A.4 The main assumptions underlying the three scenarios chosen for the study are:

| | Scenario I | Scenario II | Scenario III |
|---|---|---|---|
| World oil price in 2000 ($/bbl) | 64 | 52 | 33 |
| UK GDP growth (% per annum) | 2½ | 1½ | ½ |
| UK industrial growth | High | Low | Low |

A.5 Together with a simplified case based on 1985 constant energy prices, these scenarios were chosen to span as wide a range of views of future movements in energy prices and demands and their relativities as is considered realistic. The price assumptions in 2010 for domestic electricity resulting from these scenarios are:

| | Scenario I | Scenario II | Scenario III | 1985 Constant |
|---|---|---|---|---|
| Average (p/kWh) | 9.6 | 8.9 | 8.7 | 6.5 |
| Marginal (p/kWh) | 6.6 | 5.9 | 5.7 | 3.3 |